The VST-ISW Survey

L. Infante
Departamento de Astronomía y Astrofísica, P. Universidad Católica de Chile

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Co-Investigators: R. Assef (Ohio State University, USA), N. Padilla (P. Universidad Católica de Chile, RCH), G. Galaz P. (Universidad Católica de Chile, RCH), R. Jimenez (University of Pennsylvania, USA), D. Spergel (Princeton University, USA), F. Barrientos (P. Universidad Católica de Chile, RCH), P. Aguirre (P. Universidad Católica de Chile, RCH), H. Quintana (P. Universidad Católica de Chile, RCH), A. Reisenegger (P. Universidad Católica de Chile, RCH), M. Hilker (University of Bonn, D), S. Lopez (Universidad de Chile, RCH), M. Zoccali (P. Universidad Católica de Chile, RCH), F. Menanteau (Johns Hopkins University, USA), D. Minniti (P. Universidad Católica de Chile, RCH) T. Richtler (Universidad de Concepción RCH), N. Benitez (Instituto de Astrofisica de Andalucia, ESP), M. Moles (Instituto de Astrofisica de Andalucia, ESP), A. Jordan (ESO), T. Shanks (University of Durham UK), R. Barba (Universidad de La Serena RCH),

Abstract

We propose a southern 5000 deg^2 deep survey of galaxies in the r band to detect the Integrated Sachs-Wolfe Effect with a signal to noise ratio 40% higher than any other survey so far (*e.g.* SDSS DR4) . The aim is to determine the equation of state of the universe by cross-correlating this galaxy map with high resolution CMB anisotropy maps from existing WMAP and future Planck observations. We show that we can reach a near-maximum S/N value of the ISW effect using a *single* broad-band (r) spatially-contiguous galaxy catalogue with a mean redshift $\langle z \rangle = 1.2$ at a particular scale of the sky (0.5 deg^2). Morever, galaxy binning it is not required and therefore redshift information is not needed for all galaxies to compute the ISW effect. To cover the desired field, 64 nights in 4 years ($r_{AB} \lesssim 23.8$, 16 dark-grey 1.0 arcsec seeing nights per year) are required with VST. To maximize the output and open this survey to further science goals (ACT clusters, SZ effect, Red sequence galaxy clusters, LSBs, UCDs, Dwarf Galaxies, lenses) we will observe the same area as the approved VST ATLAS survey, which will provide de deep g band observations. The ISW results from this survey will surpass the results from SDSS, because of its depth, and be comparable to the results of the Dark Energy Survey, but 3 years earlier. This survey will be nade available to the community.

KEYWORDS: COSMOLOGY, GALAXY CLUSTERS, GALAXIES

1 The VST-ISW Survey (ISW@VST)

Recent observations have established a new standard model of cosmology. With only five basic parameters (the age of the universe, the density of matter, the density of atoms, the amplitude of primordial fluctuations, and their scale dependence), this model fits both microwave background observations probing the physical conditions in the early universe and observations of the large-scale distribution of galaxies today (Spergel et al. 2003, Spergel et al. 2006).

While remarkably simple, the new standard cosmological model is also rather bizarre. It implies that protons, neutrons and electrons comprise only 4% of the energy density of the universe. Cosmologists believe that most of the mass in the universe is composed of weakly interacting subatomic particles (“the dark matter”) which have never been directly detected. We also believe that all of the matter comprises only 26% of the total energy density of the universe, while the remainder is in some kind of energy associated with empty space (“the dark energy”).

As the universe expands, light travels from the last scattering surface trespassing the matter structure along its path. Since this expansion is accelerated in some cosmics epochs, features are imprinted in the Cosmic Microwave Background (CMB) radiation, modifying its original gaussianity. This radiation as is observed is not isotropic (WMAP, Spergel et.al.,2006). Anisotropies are generated by several mechanisms along the radiation path. Among the best known are lensing, the Sunyaev-Zel'dovic (SZ) and the Integrated Sachs-Wolfe effect (ISW, Sachs & Wolfe, 1967). In this work, we propose to measure anisotropies generated by the ISW effect. The ISW effect arises as follows. As the Universe expands it weakens the gravitational potential wells associated with the clustering of galaxies. A photon traveling through such region gets an energy boost as it falls in the well, but because the well is shallower by the time the photon comes out it loses less energy than what it had gained. This will cause large scale anisotropies in the CMB. We will disentangle the lensing and SZ from ISW anisotropies and we will provide high signal to noise (S/N) value for Ω_λ and Ω_m.

Given the CMB temperature resolution achieved with modern microwave explorers such as WMAP (existing) and PLANCK (future), it is possible to cross correlate the local ($z \lesssim 1.2$) matter structure with the observed CMB structure. The cross correlation amplitude depends on the acceleration modulus which in turn depends on the dark energy (DE) density. Therefore, to unambiguously measure the signal, we propose a large, deep survey of galaxies. Below we show that $5000 deg^2$, in one band, down to $r \approx 23.8$, on 0.5 degrees scales and no redshift information provides the large scale data (i.e. galaxy map) to clearly measure the ISW signal.

The cross correlation analysis as shown in the following paragraphs has not been published so far. More details about the proposed survey, as well as of Value Added Projects, can be found in the project Redbook: http://www.astro.puc.cl/linfante/VST-ISW

1.1 Cross Correlation analysis

The ISW effect dominates the cross correlation signal at an angular scale of $\theta \gtrsim 1$deg, while at lower angular scales the signal is dominated by the SZ effect. The cross correlation function of fields A and B, which we will call $\omega_{AB}(\theta)$, can be written in terms of the angular power spectrum multipoles, $C_{AB}(l)$, by expanding it on Legendre polynomials,

$$\omega_{AB}(\theta) \;=\; \sum_{l=0}^{\infty} \frac{(2l+1)}{4\pi}\; C_{AB}(l)\; P_l(\cos\theta),$$

where P_l is the Legendre polynomial of order l. It is possible to show that for small angles, or large l, (Afshordi et al. 2004, Cooray 2002)

$$C_{AB}(l) \;=\; \int_0^{\infty} \frac{dr}{r^2}\; P(k)\; W^A(k,r)\; W^B(k,r),$$

where $P(k)$ is the initial power spectrum of matter, k is given by $k = \frac{l+1/2}{r}$, and $W^X(k,r)$ is the window function of the field X. This approximation holds up to a good degree of accuracy for $l \geq 2$. According to Afshordi et. al. (2004), the error is 10% for $l = 2$ and falls like l^{-2}. It should be noted that for these estimations, we will use the initial matter power spectrum given by Bond & Efsthathiou (1984).

The window function of the anisotropy field generated by the ISW effect can be written as $W^{ISW}(r,k) = -3T_0\, \frac{\Omega_m}{k^2}\, \frac{H_0^2}{c^3}\, \frac{\partial F(z)}{\partial \tau}$, where T_0 is the mean temperature of the CMB, Ω_m is the matter density of the universe in units of the critical density, H_0 is Hubble's constant, c is the speed of light, τ is the conformal time ($dt = d\tau/(1+z)$) and $F(z)$ is the growth factor of the gravitational potential. An analytical expression for $\partial F/\partial\tau$ is given by Lahav (1991), which will be used for this calculation.

For the galaxy field, it is possible to show that $W^g = b_g\, \frac{H(z)}{c}\, D(z)\; n(z)$, where b_g is the bias factor, that we will assume to be 1 since the S/N estimations will not depend on this factor, $H(z)$ is the Hubble parameter as a function of redshift, $D(z)$ is the growth factor of the initial matter over densities in Fourier space, and $n(z)$ is the galaxy density distribution, which will depend directly on the characteristics of the observations.

Afshordi et. al. (2004) showed that the error on each multipole of the angular power spectrum is given by

$$\sigma^2_{C_{gT}} \;=\; \frac{1}{f_{sky}(2l+1)}\;\left\{C^2_{gT}(l) + C_{TT}(l)\left[C_{gg}(l) + \frac{1}{\bar{N}}\right]\right\},$$

with $C_{TT}(l)$ being the multipoles of the temperature anisotropy field angular power spectrum, $C_{gg}(l)$ the ones of the galaxy field angular power spectrum and $C_{gT}(l)$ the ones of the cross power spectrum. $\bar{N}$ is the mean number of galaxies per steradian on the survey, the 'Shot Noise', and f_{sky} is the fraction of the sky used for the cross correlation. This can be propagated to the cross correlation function, so that

$$\sigma^2_{\omega_{gT}} \;=\; \sum_l \frac{(2l+1)}{f_{sky}(4\pi)^2}\;P^2_l(\cos\theta)\;\left\{C^2_{gT}(l) + C_{TT}(l)\left[C_{gg}(l) + \frac{1}{\bar{N}}\right]\right\}.$$

1.2 Why Single scale measurements.

Doing an analysis similar to the one used to predict the error on the cross correlation, is possible to show that the covariance between the measurements on two different angular scales, θ_1 and θ_2, can be estimated with the following expression

$$Cov(\theta_1,\theta_2) \;=\; \sum_l \frac{(2l+1)}{f_{sky}(4\pi)^2}\;P_l(\cos\theta_1)\;P_l(\cos\theta_2)\;\left\{C^2_{gT}(l) + C_{TT}(l)\left[C_{gg}(l) + \frac{1}{\bar{N}}\right]\right\},$$

which, as expected, converges to the expression for the variance when $\theta_1 = \theta_2$. Unless one of the angular scales is very large, case on which the respective correlation signal will be very small, the covariance has a value similar to that of the variance. So, the overall signal to noise, considering all angular scales, will be extremely close to the maximum, since other angular scales will add a very little amount to it.

1.3 Signal to noise ratio.

Hence, using the above formalism we can estimate the S/N of a certain measurement of the ISW cross correlation function at a certain angular scale.

We plan to map galaxies over approximately 5000 deg^2 of the southern sky in the r band. The left panel of Fig. 1 shows the expected redshift distribution for such a survey. The right panel of Fig. 1 shows its predicted cross correlation function S/N and also the one predicted for the DES and for the DR5 of the SDSS, assuming a Λ CDM cosmology ($\Omega_M = 0.3$,$\Omega_\lambda = 0.7$,$\Omega_k = 0$, $H_0 = 70$ and $w = -1$). The predicted S/N of this survey is indeed slightly higher than the one of the DES, and significantly higher by nearly 40% than the one of the DR5. No other projected or on-going survey will get closer to this.

The estimate of the S/N presented above does not consider the SZ effect. This will affect scales below 1deg, including a little decrement on the peak S/N. For this reason we will focus on the scale of 1 degree even though it is slightly away from the peak S/N. In a few more years the South Pole telescope will measure this effect on the same region on which the DES is programmed. In principle it should be possible with this measurements to correct for this effect and recover the peak.

1.4 Why redshifts and multi-bands are not necessary

As stated on the previous paragraphs, to detect the ISW effect we only need to detect galaxies, so multi-band observations will not yield an improvement in general. The only way multi band photometry could help us is by the use of photometric redshifts. If we divide our sample in various redshift slices, each slice would be independent of the others and have a smaller signal to noise than the maximum of the right panel of Fig. 1. The total signal to noise would be the addition in quadrature of all the individual ones, and one would expect a higher overall value. We test this for the proposed survey, assuming that we can use slices of 0.1 units of redshift up to a redshift of 2 for the cross correlation with negligible shot noise on the matter power spectrum. The top panel of Fig. 2 shows, with a dashed line, the overall added S/N, and it is, indeed, higher, even though just slightly, than the one obtained without the redshift slices. But in order to get such accurate photometric redshifts, we would need

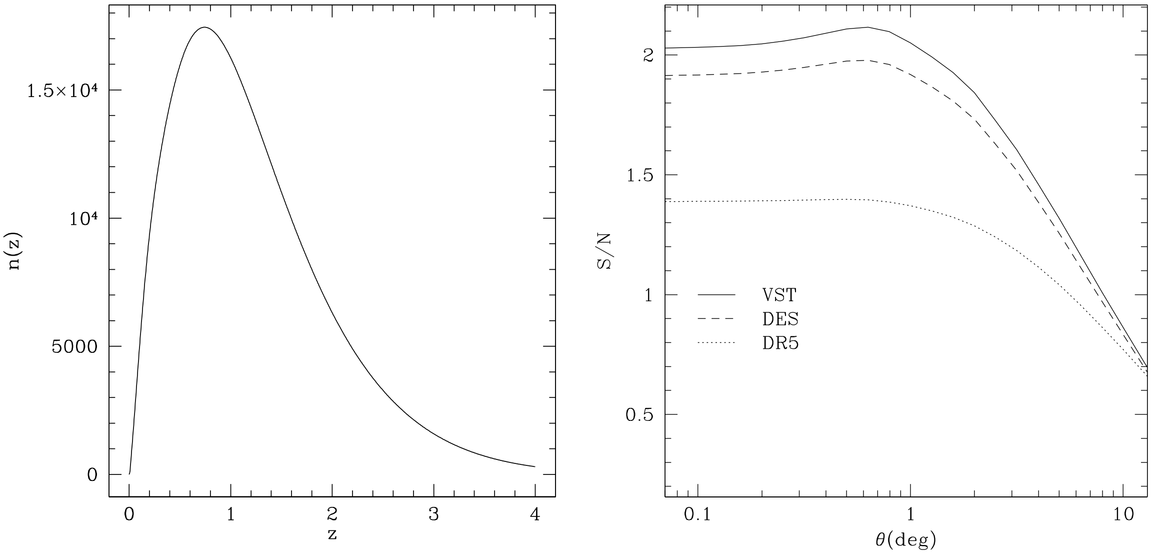

Figure 1: Fig. 1: Expected galaxy redshift distribution of the survey (left) and cross correlation S/N prediction for the proposed survey, DES and SDSS's DR5 (right). Note how the expected S/N is much higher than the one expected for the DR5. The expected S/N of the DES is of the same order but slightly lower. The redshift distribution is calculated assuming a Schechter Luminosity Function, $\Phi(M)$ (LF) for the galaxies corresponding to $M = -22.7$ and $\alpha = -1.33$. These parameters correspond to the r-Band $z = 1$ LF (Gabasch et al., 2006, A&A, 448, 101) estimated for FORS galaxies. The relation used to calculate the redshift distribution is $\frac{dn}{dz}(z) \propto \int_{M_{high}}^{M_{low}(z)} \Phi(M) dM \frac{dV}{dz}$,where we set the maximum galaxy luminosity at r-band $M_{high} = -25$ and the lower luminosity limit corresponds to the chosen magnitude limit, $m_{lim} = -23.8$, $M_{low}(z) = m_{lim} - 25 - 5\log(r(z))$. We assume $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ when calculating dV/dz and $r(z)$.

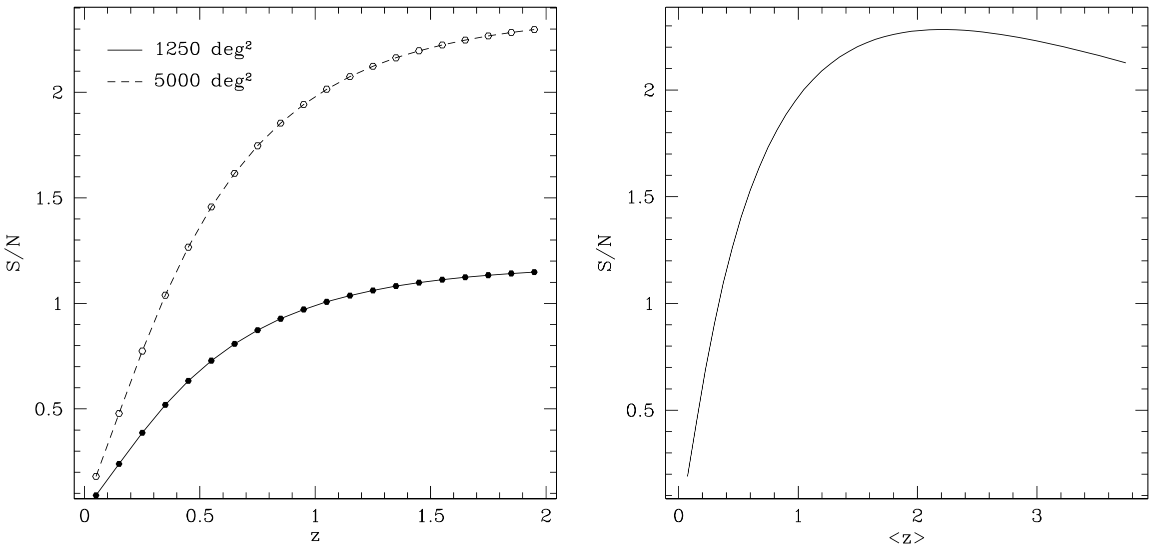

Figure 2: Fig. 2 **Top**: Accumulated S/N as a function of redshift, adding slices of 0.1 units of redshift with negligible shot noise up to redshift of 2. The dashed line assumes that the survey covers 5000 deg^2 while the solid line assumes it covers only a fourth part of that, what we would actually get with 4 bands imaging. **Bottom**: Maximum signal to noise of the correlation function as a function of the mean redshift of the survey. Our proposal considers a mean redshift of 1.2, yielding a S/N close to the peak value.

at least 4 photometric bands, which in practice would reduce by a factor of 4 the fraction of the sky covered by the survey. Fig. 2 (top panel) shows in a solid line the expected results considering only a fourth of the 5000 square degrees proposed. The S/N is roughly 0.5 times the maximum of Fig. 1. In conclusion, multi band observations will not yield a significant improvement to the measurement.

1.5 Optimum mean redshift and limiting magnitude.

The ISW effect is driven by the accelerated expansion of the universe. Extremely distant galaxies are not affected at all by this accelerated expansion, so they will not produce anisotropies on the CMB. If our survey were to be extremely deep, the cross-correlation signal to noise will not be optimum, since distant galaxies will add noise to the measurement. Fig. 2 (bottom panel) shows the signal to noise as a function of the mean redshift of the survey at a scale of 0.5 deg. The maximum is for a mean redshift of ≈ 2 and the distribution is fairly flat around it. The mean redshift of the proposed survey is approximately 1.2 (see Fig. 1 for the redshift distribution), which will yield almost the maximum possible S/N. In Fig. 3 we show the average redshift of a sample of galaxies ($\langle z \rangle$) as a function of the magnitude limit, r_{lim}. Our estimates are based on a characteristic Schechter magnitude, M^*, consistent with recent estimates at $z \simeq 1$ (Gabasch et al., 2006). We show that adopting a magnitude limit of $r_{AB} = 23.8$ in the proposed survey, the mean redshift is $\langle z \rangle = 1.2$, which is optimum as shown in Fig. 2. Notice that these predictions are based on theoretical Omegacam performance, so even in the extreme case of overestimated the brightness of a M^* galaxy at $z = 1$ by 0.7 magnitudes, the proposed survey will still be able to provide a signal-to-noise similar than the one expected to be achieved by DES, but three years earlier.

1.6 Comparison with Previous Studies

Afshordi (2004) carried out predictions very similar to the ones presented in this proposal. The maximum possible S/N for a survey like the one proposed here can be calculated from his results to be ~ 2.7. This maximum, calculated in spherical harmonics space rather than in configuration space, considers redshift bins and all angular scales, is consistent with our $S/N = 2.2$ estimate. Previous

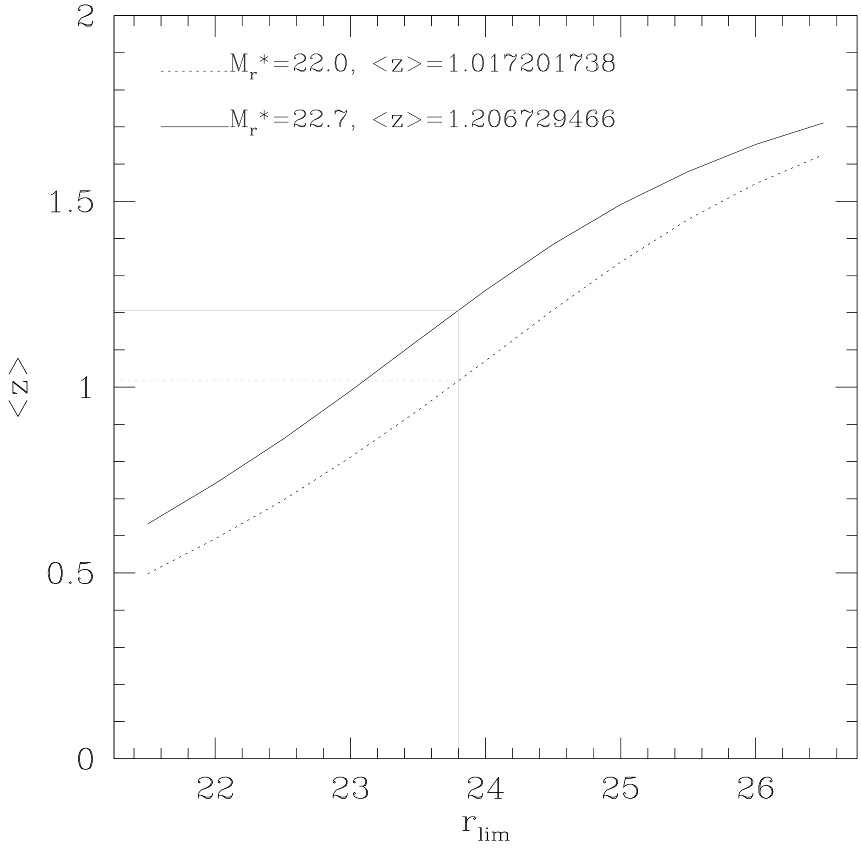

Figure 3: Fig. 3 Average redshift of a sample of galaxies ($\langle z \rangle$) as a function of the r band magnitude limit, r_{lim}. Black solid line corresponds to a characteristic Schechter magnitude, M^*, consistent with recent estimates at $z \simeq 1$ (Gabasch et al., 2006), and black dotted line shows the results for a different, lower value of M^*. The gray horizontal lines indicate the average redshifts corresponding to the adopted magnitude limit of $r_{AB} = 23.8$ in the proposed survey, which is $\langle z \rangle = 1.2$ for the measured value of M^*, and only diminishes to $\langle z \rangle = 1.0$ when introducing a lower characteristic luminosity.lower characteristic luminosity.

measurements of the ISW have been carried out using different surveys. For example, Fosalba et al., (2003) used SDSS DR1 and APM data, Afshordi et al. (2004) used 2MASS and recently Cabre et al. (2004) used SDSS DR4 data. Compared to theoretical values, these results tend to have higher S/N by factors ~ 3, possibly due to contamination. For instance, Afshordi et al. (2004), obtained a 2.5-σ detection of this effect. However, if one considering galactic plane contamination the value goes down to a 1.7-σ. Fosalba et al. (2003) and Cabre et al., (2004) obtained a S/N of 3.3 and a 4.7 respectively, where the difference with this estimations mostly comes from the differences in the covariance estimations between different angular scales.

1.7 Immediate Objective

The main objective of this program is to produce a catalogue of southern objects over $5000deg^2$ in the r band to determine with a very high accuracy, independent from existing methods (*e.g.* weak lensing, WMAP, Supernovae), the equation of state of the universe. This survey will be done in 4 years with the VST using 240 seconds exposure time in the r band. For this, 16 photometric nights per year of observing time with median seeing ($\lesssim 1$) are required. We have designed a plan to produce results earlier than any competing survey. The survey area will be the same as the approved ESO public survey VST ATLAS. Arrangements have been carried out so that we provide the deep r band observations and the VST ATLAS provide a deep 120 seconds g band survey. Having deep g and r bands in hand, a number of other programs are possible. In addition, negotiations are in progress to add IR J and H bands with VISTA. The finished product, in 2010, will be a deep (2 magnitudes deeper than SDSS) survey in four optical and infrared bands opened publicly to the astronomical community. Such survey will provide targets for the second generation VLT instruments and to the planned $25 - 100m$ class telescopes.

1.8 Survey Area and layout.

In Fig. 1 the survey boundaries are depicted. Other survey boundaries are also shown. We will survey the VST ATLAS area (4500 deg^2) plus a contiguous 500 deg^2 field wich overlaps with the planned Atacama Cosmology Telescope (ACT) strip. In this way we maximize year coverage and overlap with other surveys. Surveys that map different areas of the sky are completly independent for measuring the cross correlation signal of the ISW effect. This means that the detection of the ISW effect with this survey will not only have a higher S/N than for any other projected survey, but will also be complementary with them.

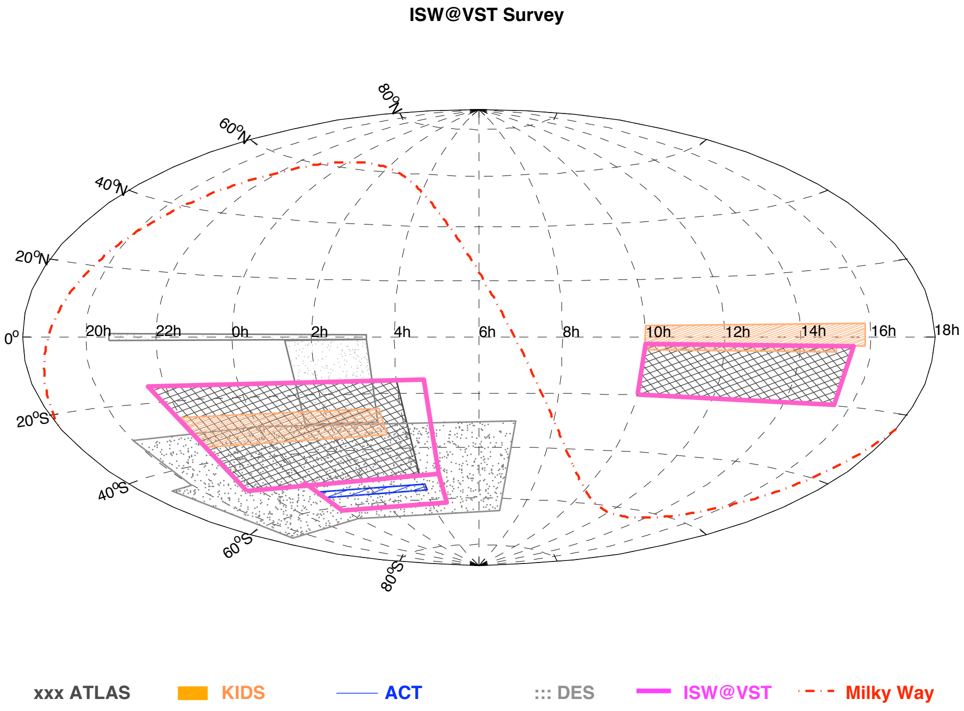

Figure 4: Fig. 4 An "aitoff" representation of the ISW@VST survey boundaries. For comparison, the survey area and layout of other surveys are also shown.

1.9 Observations and Survey Strategy.

Observations will follow the order shown in Table 1.

Run	Period	Month	Time	Nights	Moon
A	79	April	40	4	$\leq$ —7—
B	79	Sept	47.5	5	$\leq$ —7—
C	80	Oct	32	4	$\leq$ —7—
D	80	Nov	24	3	$\leq$ —7—
E	81	April	40	4	$\leq$ —7—
F	81	Sept	47.5	5	$\leq$ —7—
G	82	Oct	40	5	$\leq$ —7—
H	82	Nov	16	2	$\leq$ —7—
I	83	April	40	4	$\leq$ —7—
J	83	Sept	42.75	4.5	$\leq$ —7—
K	84	Oct	40	5	$\leq$ —7—
L	84	Nov	20	2.5	$\leq$ —7—
M	85	Sept	50	5	$\leq$ —7—
N	85	Oct	57	6	$\leq$ —7—
O	86	Nov	40	5	$\leq$ —7—

Table 1: Observations Strategy: including calibration time.

Run	α(J2000)	δ(J2000)	Add.info
A	12 45 00.0	-17 54 00	RA 10h00:15h30, Dec -15.7:-20.1
B	01 15 00.0	-17 12 00.0	RA 21h30:4h40, Dec -15:-19.4
C	01 15 00.0	-20 16 48	RA 21h30:4h40, Dec -19.4:-21.16
D	2 16 00.0	-55 16 48	RA 23h52:4h40, Dec -52.64:-57.92
E	12 45 00.0	-13 30 00	RA 10h00:15h30, Dec -11.3:-15.7
F	01 15 00.0	-23 21 36	RA 21h30:4h40, Dec -21.16:-25.56
G	01 15 00.0	-27 19 12	RA 21h30:4h40, Dec -25.56:-29.08
H	2 16 00.0	-51 28 12	RA 23h52:4h40, Dec -50:-52.94
I	12 45 00.0	-9 32 24	RA 10h00:15h30, Dec -7.78:-11.3
J	01 15 00.0	-31 16 48	RA 21h30:4h40, Dec -29.08:-33.48
K	01 15 00.0	-35 40 48	RA 21h30:4h40, Dec -33.48:-37.88
L	2 16 00.0	-60 7 12	RA 23h52:4h40, Dec -57.92:-62.32
M	12 45 00.0	-5 8 24	RA 10h00:15h30, Dec -2.5:-7.78
N	01 15 00.0	-40 57 36	RA 21h30:4h40, Dec -37.88:-44.04
O	01 15 00.0	-47 07 12	RA 21h30:4h40, Dec -44.04:-50.2

Table 2: Observations Strips

1.9.1 Lunar Phase

In order to reach a photometric signal to noise ratio of 10 in the r band for a $r_{AB} = 23.8$ object we need a lunar illumination less than 50%, which is ~ 7 nights before or after new moon.

1.9.2 Integration time and number of nights

As shown above, the ISW cross correlation signal to noise ratio is maximized with a catalogue whose mean redshift is 1.2. As show in Fig. 4 using the VST this mean redshift is achieved with a limiting magnitude of $r_{AB} = 23.8$. We used the VOCET exposure time calculator to estimate that 240secs exposure time per exposure to reach a a S/N ratio of 10. Now we estimate the total time required to survey $5000deg^2$ in the r band to the above depth. We assume the following: no binning (0.21×0.21pixels; 52secs of overheads per exposure (Valentijn, priv. comm.); 10% overlap per pointing which implies an effective area per pointing of $0.78deg^2$; 9hrs per night between astronomical twilights (average of 8hrs per night Oct-Mar and 10hrs Apr-Sep); Dark time; 240secs in r results in $9.6deg^2$ per hour. Therefore, to cover $5000deg^2$ we need 58 nights in four years. Time allocation should be $< |7|$ nights from new moon. We shall need to allow 10% more for calibration observations, implying that the total number of nights that will be needed to cover $5000deg^2$ is 64 dark to grey nights; 16 nights per year.

1.10 Resources

We have reached an agreement with the VST ATLAS and VISTA teams to use their data management system. What follows are the VST ATLAS plans adapted to the current survey. For a detailed description, please refer to the VST ATLAS proposal and references herewith. In short, the current survey and the VST ATLAS will use the VISTA Data Flow System (VDFS; Emerson et al. 2004, eds. P.J. Quinn & A. Bridger, Proc. SPIE, vol. 5493, 401 - Irwin et al. 2004, eds. P.J. Quinn & A. Bridger, Proc. SPIE, vol. 5493, 411 - Hambly et al. 2004, eds. P.J. Quinn & A. Bridger, Proc. SPIE, vol. 5493, 423) for all aspects of data management, including: pipeline processing and management; delivery of agreed data products; production of a purpose-built VO compliant science archive with advanced data mining services which will be duplicated at PUC. Standardized data products produced by VDFS will be delivered to the community, with a copy remaining at the point of origin (in the Science Archive run by WFAU in Edinburgh) and PUC. The VDFS is sufficiently flexible as to be applicable to any imaging survey project requiring an end-to-end (instrument to end-user) data management system. The data flow system will be produced by the current VDFS team, who will be responsible for the main data products and for delivering data products to agreed specification to the ESO Science Archive. The VDFS pipeline will be used for all processing. This includes the following processing steps: instrumental signature removal - bias, non-linearity, dark, flat, fringe, cross-talk, persistence; sky background tracking and adjustment during image stacking and mosaicing; combining frames; consistent internal photometric calibration to put observations on a uniform internal system; standard catalogue generation including astrometric, photometric and morphological shape descriptors and derived Data Quality Control(DQC) information, all with appropriate error estimates; accurate WCS astrometric calibration stored in FITS headers; nightly photometric calibration; propagation of error arrays; nightly average extinction measurements in relevant pass bands.

Sufficient resources for new processing, analysis and archival hardware will be provided by Fondap II in the next 5 years, starting in 2007. A postdoctoral fellow, a research assistant and a computer analyst will be hired to work for this program, based at PUC.

1.11 The VST ATLAS Collaboration

This survey will be carried out in collaboration with the VST ATLAS survey. The VST ATLAS will survey in three years 4500 deg^2 in five band passes, u, g, r, i, z. The proposed plan is to use Chilean VST time to make the deep r-band (240secs) observations and increase the ATLAS exposure time in another band, possibly, g, from 60 to 120secs. The combined ISW@VST and VST-ATLAS surveys offer the unprecedented opportunity to develop collaborative projects on two deep band passes over 4500 deg^2. If approved, this project will be a Centre for Astrophysics Key Project, funded by Fondap, Conicyt, Chile. The PI of this proposal is the PI of the Fondap ”Birth and evolution of Structures in the Universe” area. The current Fondap program will be evaluated during 2006. We are confident that the funding for the new Centre for Astrophysics program will be extended for 5 more years. This survey will be made available to the community.

2 VALUE ADDED PROJECTS

There are a number of independent projects that can be carried out using the current survey data and the data provided by the VST-ATLAS survey. In turn, we describe a sample of them

2.1 Weak lensing in the ACT strip

P.I.: David Spergel and Raul Jimenez

Abstract: We wish to obtain $r'-$band images of the Atacama Cosmology Telescope (ACT) survey strip with OmegaCam on VST. ACT is a 6-meter mm-wave telescope under construction in Cerro Toco, next to the ALMA site, with first light scheduled in fall 2006. ACT will discover about 2000 clusters in a region of 200 square degrees using the Sunyaev-Zeldovich effect. The VST imaging will allow us to measure shapes for ≈ 107 galaxies over the ACT strip, which will be used to produce high-accuracy mass measurements of the clusters via the weak gravitational lensing they induce on the background galaxies. The ACT SZ data combined with weak lensing mass calibration will yield strong constraints on the dark energy equation of state. With its superb seeing and wide-field OmegaCam imaging, VST will be the best Southern instrument for weak lensing. The power of the weak lensing data will be increased by photometric redshifts obtained from Blanco (g, i, z) and SALT telescope (U). In addition, we will have SALT spectroscopy for a selected sample of galaxies in the ACT strip which will be used as a training set for photometric redshifts. The completed ACT lensing data will therefore be among the best available for measuring galaxy evolution and "cosmic shear" as well as cluster masses. Further, we have recently demonstrated how the physical conditions in galaxy clusters can be most efficiently recovered by using combined mm and weak lensing observations, without the need of Xray data.

The ACT strip is at a declination of -55 degrees and therefore cannot be observed from any telescope in the Southern Hemisphere.

The ACT Survey Project Recent observations have established a new standard model of cosmology. With only five basic parameters (the age of the universe, the density of matter, the density of atoms, the amplitude of primordial fluctuations, and their scale dependence), this model fits both microwave background observations probing the physical conditions in the early universe and observations of the large-scale distribution of galaxies today (Spergel et al. 2003).

While remarkably simple, the new standard cosmological model is also rather bizarre. It implies that protons, neutrons and electrons comprise only 5% of the energy density of the universe. Cosmologists believe that most of the mass in the universe is composed of weakly interacting subatomic particles ("the dark matter") which has never been directly detected. We also believe that all of the matter comprises only 25% of the total energy density of the universe, while the remainder is some kind of energy associated with empty space ("the dark energy").

As is often true in science, answering old questions such as "What is the shape of the universe?", "What is the age of the universe?" and "What seeds galaxy formation?" has led to new questions: "What is the dark energy?", "What is the dark matter?" and "How do galaxies emerge from fluctuations in the early universe?" We have embarked on an experimental program that aims to address these new questions. WMAP has measured the primordial microwave background radiation over the full sky with angular resolution of $20'$; we are planning to map a smaller portion of the sky (200 square degrees) at much finer angular scales ($2'$) and with much higher sensitivity using the new Atacama Cosmology Telescope (ACT)[1] and with extensive optical and Xray follow-up. This project is a NSF-funded collaboration between Princeton, University of Pennsylvania, Rutgers, Goddard Space Flight Center, National Institute of Standards and Technology, and **Pontificia Universidad Catolica de Chile (Chile)**. The ACT collaboration is building a custom-designed microwave telescope outfitted with novel superconducting bolometer-array detectors. It will measure the microwave sky from the Atacama Desert, with the goal of probing a number of fundamental properties of the universe such as the nature of dark energy, the mass of the neutrino, and the origin of the missing baryons. This proposal will greatly enhance the first of these goals: unveiling the nature of dark energy.

The Atacama Cosmology Telescope will survey a 360×2 squaredegree region of the Southern sky in three (145, 220 and 270 GHz) mm bands at resolutions ranging from 0.9 to 1.7 arcminutes, with target sensitivity of 2 μK per pixel. Of the full ACT survey region, the cleanest 100×2 square degrees will be used for cosmology studies and will have optical and Xray follow up. ACT is currently on schedule for engineering observations in the second half of 2006, with full science observations in 2007 and 2008.

In addition to the mm observations, there are four ACT follow-up surveys: optical imaging (U)

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[1] For more information, see `http: //www.hep.upenn.edu/act/`

with the Southern African Large Telescope (SALT) (guaranteed); spectroscopic survey of 200 galaxy clusters in the ACT strip with SALT (guaranteed) and the Blanco Cosmology Survey with already 20 sq. deg. of photometry in the ACT strip obtained in giz. Thirty nights of SALT time per year for the next four years are already granted.

VST imaging of the ACT strip would have much better seeing than expected from SALT, measuring faint-galaxy shapes well enough to produce weak gravitational lensing measurements of the dark-matter distribution. The 2006 time requested here will suffice to image 100% of the ACT prime area. This will mean that by January 2007 we can have these data analysed.

Galaxy clusters and dark energy

There are two observable consequences of dark energy: the evolution of the scale factor, $a(t)$, and the growth rate of structure, $D(z)$. Observations that constrain the distance/redshift relationship (luminosity distance observations, angular diameter distance observations, and volume tests) measure $a(t)$ and probe the dark energy properties through the Friedmann equation. Observations that measure the evolution of structure probe the dark energy properties through the evolution of linear perturbations, $D(z)$.

Counts of galaxy clusters $N(M, z)$ as a function of cluster mass M and redshift z are sensitive to both $a(t)$, through the volume element, and $D(z)$, through cluster growth, and hence are a very strong complement to supernova and CMB data, which measure only $a(t)$. There are analytic predictions for $N(M, z)$ which can be refined by N-body gravitational simulations. The number of massive clusters has an exponential dependence upon cosmological parameters, making it a potentially very sensitive test. Galaxy clusters can be detected by their optical galaxy counts; by the x-ray emission from intra-cluster gas; and, with the advent of ACT, by their SZ effect on the CMB. The challenge for each of these methods is to understand the relation of the observable quantity (galaxy counts, x-ray flux/temperature, or SZ decrement) to the mass of the cluster. Systematic errors in this conversion will invalidate the comparison of the observation to the N-body theory, and unfortunately the cosmological parameters are exponentially sensitive to such errors. The SZ decrement is expected to trace the mass much more closely thanthe x-ray or galaxy-count observables, because it is less sensitive to the complex behavior of cluster baryons. ACT will produce the first SZ-based cluster census.

Weak gravitational lensing measures (projected) mass in a manner that is completely independent of baryonic effects. Weak lensing data will therefore allow us to calibrate the ACT cluster mass scale even more precisely, leading to stronger dark-energy constraints. *The aim of this proposal is to use OmegaCam/VST weak lensing observations to obtain more accurate cluster mass determinations and improve the ACT dark-energy constraints.*

We plot below the expected cluster-mass detection threshold for the ACT SZ survey vs redshift. Each 10σ weak lensing detection can also be considered a 10% measurement of the mass of that cluster, so we see that the lensing data will provide such information for most of the $z < 0.7$ clusters seen by ACT. The *overall* mass scale can be determined even more accurately by averaging the lensing signals for large numbers of SZ-detected clusters, bringing the mass-scale uncertainty down to the few-percent level, far better than any current cluster survey.

The ACT survey will bring together for the first time SZ, galaxy-count, velocity-dispersion and weak lensing data for a common sample of significant size. While other SZ projects exist, South Pole Telescope and APEX, ACT is the only one with guaranteed optical follow-up (SALT). The addition of weak lensing data will undoubtedly lead to much better understanding of the evolution of galaxy clusters and the relation of these different observables to each other. The weak lensing data will serve to anchor all of these methods to the underlying mass.

Weak lensing projects

The proposed observations will allow many weak lensing (WL) studies beyond the calibration of the ACT cluster mass scale. While the ACT strip will not be the largest WL dataset upon its completion, the variety of other data available from the ACT surveys will make it uniquely powerful. Measurements of the WL power spectrum on the sky—"cosmic shear"—are another method to constrain cosmological parameters (e.g. Jarvis, Jain, & Bernstein 2005). We expect this VST observing season to yield $\approx 180\ \mathrm{deg}^2$ of lensing data. This will be similar to the largest-area weak lensing survey at the time of its completion, for instance the 200-night CFH Legacy Survey currently underway plans to survey 180 square degrees at a slightly greater depth. However the SALT data will produce superior photometric redshift information on this strip, improving the accuracy of our cosmic-shear data. Further cosmological tests are possible by measuring the strength of the cluster lensing signal as a function of the source galaxy redshift (Jain & Taylor 2003); the ACT strip may be the first with sufficient signal and photo-z accuracy to attempt this test.

Other investigations become possible by cross-correlating the lensing information with features in the optical/x-ray/UV/mm-wave ACT imaging. For example one can measure the evolution of galaxy halo masses by determining the "galaxy-galaxy lensing" signal around foreground galaxies identified by photo-z, type, and color. The ACT data may also present the first opportunity to detect lensing of the CMB; we could cross-correlate this CMB lensing pattern with the VST galaxy lensing maps in order to verify the reality of both, and ultimately use the cross-correlation to constrain cosmology and the growth of structure.

A precursor to future surveys

The ACT surveys will be uniquely powerful resource for galaxy cluster studies, mass measurements and investigations that measure the correlation of mass and shear with the foreground galaxy and cluster distributions. Some of the strongest available dark energy constraints will result, and the experience from these data will guide the next generation of lensing experiments such as the Large Synoptic Survey Telescope (LSST). Our proposed lensing survey will be unique as it can be directly cross-correlated with CMB lensing, thermal SZmeasurements and kinetic SZ measurements. No other survey exist that offers such a "pan-chromatic" view of the universe in the redshift range $0.2 < z < 1.2$, plus the "achromatic" view offered by weak lensing. The ACT experience will certainly lead to the formulation of new questions for larger-scale panchromatic surveys.

Determining the nature of feedback and the state of icm gas

here I will write about the Sealfon et al. paper and add a figure from that paper.

Technical description:

ACT will survey the full right ascension range for a strip 2 degrees wide centered at fixed declination $-55°$. The highest-quality data (due to Galactic contamination and seasonal effects at the Atacama site) will be the segment from RA 23:52–04:05; this is the region to be targeted by SALT and is hence the target region for VST. Observations at low airmass are preferred since PSF quality is paramount (see below). Dates from Sep 02 to Dec 10 have some portion of this region to be accessible at airmass ≤ 1.5 for nearly the full night.

All of the imaging will be done in the g filter. Redder filters are less efficient because of rapidly brightening sky; bluer filters are less efficient because the seeing degrades (slowly) and are more susceptible to moonlight. The galaxies we wish to use as lensing sources are all fainter than the night sky, so lunar phases brighter than 9 days incur a substantial penalty for sky noise (when the moon is up).

Tests of our galaxy shape measurement software suggest that the PSF must be 2.6 pixels wide or larger before under-sampling inhibits the measurement. Hence the 0.2 arcsec pixel scale of the camera is fine enough for nearly all conditions.

We aim to survey as rapidly as possible without undue overhead; given the 75–90 s readout time of the OmegaCam camera, we select a 200 s exposure time. We also need 3 exposures on each sky location in order to robustly eliminate defects and cosmic rays, yielding a total of 600 s integration on each sky location.

We use the VST g-band zero-point and expected sky brightness to calculate the noise levels in 600 s images. We can combine these expected noise levels with an estimated mean VST seeing FWHM to produce simulated images by degrading the Hubble GOODS and Ultra Deep Fields. By running our shape measurement software on these images we can then estimate the number of useful shapes measured per square arcminute, which is the figure of merit for weak lensing observations, as it determines the noise level in mass reconstructions. We findthat in $0.7''$ seeing, we will obtain 14 galaxies arcmin^{-2} from the OmegaCam imaging, which is quite good. By comparison, the same exposure time with seeing of 0.9 or $1.1''$ would obtain only 8.4 or 5.5 galaxies per square arcminute. This is the reason for requesting VST time, as opposed to using the SALT imaging or Blanco MOSAIC for this task. The signal-to-noise of our mass determinations scales somewhere between the square-root and linearlywith this figure, so VST is a substantial advance if we assume a median seeing of $0.7''$ FWHM.

The same simulations show that the gain with additional exposure time would be slight: less than 10% gain for extending the exposures to 300 s, for example. Hence we find the 3 × 200 s scheme optimal. Counting readout overheads, we can cover 5 $\mathrm{deg}^2\ \mathrm{hr}^{-1}$, or 50 deg^2 per night. We request three nights, sufficient for 150 square degrees of imaging this semester.

2.2 The number density of LSBs and VLSBs

P.I.: Gaspar Galaz

2.2.1 Background and rationale

Low surface brightness galaxies (LSBs) are usually defined as galaxies with central surface brightness $\mu_0(B) \geq 22.0$ mag arcsec^{-2}. In practice, they discovery started a new field of research in Astronomy after some observational facts indicate several enigmatic features of these galaxies:

1. their number density in the universe appear to be as large as that for high surface brightness galaxies (HSBs), with the additional problem that bonna fide LSBs are only detectable in the *local* universe (e.g. $z \leq 0.1$), in part due to the rapid decrease of their already faint surface brightness as a consequence of the cosmological dimming by the $(1+z)^{-4}$ factor. The accurate determination of their number density could still have a profound impact on the value of the matter density in our universe.

2. The evolutionary path of LSBs is still a mystery, considering that they have a small stellar formation rate (SFR), usually less than 2 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$, and even though they present in many cases a significant fraction of old stellar populations, challenging the measured small SFRs.

3. The rotation curves of LSBs indicate that they have a significant fraction of dark matter, compared to HSB spirals. Although several clues have been followed, in particular studying the Tully-Fisher relation for LSBs, a clear answer about the nature of the dynamics of LSBs is not at all clear.

4. Recent discoveries point that LSBs have a very small fraction of molecular gas (e.g. H_2, CO), but a large fraction of atomic gas (e.g. H), adding the question on how such an efficiency in forming a stellar system with small density but so less residual molecular gas.

The VLT Survey Telescope (VST) would allow an unprecedent improvement in the study of LSBs, adding valuable knowledge to one or several of the above questions. Its combined sky coverage and potential depth provide the possibility of discover both *very* low surface brightness galaxies (VLSBs, $\mu(B) \geq 24.0$ mag arcsec^{-2}) at low redshift ($cz < 5000$ km/s), not discovered by surveys already large in area but bright in surface brightness limit (e.g. Sloan, 2dF), as well as traditional LSBs ($22.0 \leq \mu(B) < 24.0$ mag arcsec^{-2}) up to $z \sim 0.15$. Following computations of the spatial density of LSBs (see for example Dalcanton et al. 1997, O'Neil et al. 2000), it is expected that in 5000 deg^2, we find *at least* 20500 VLSBs in the range $24.0 \leq \mu(B) < 26.0$ mag arcsec^{-2}), with scale lengths of > 8 arcsec, plus around the same figure for LSBs with the same scale lengths. This number will allow:

- To compute with high accuracy the number density of galaxies as a function of the surface brightness, improving significantly the current picture of the spatial distribution of LSBs and VLSBs (see O'Neil et al. 1999), establishing at last the contribution of LSBs and VLSBs to the baryonic density of the universe.

- To trace the evolution of the surface brightness and therefore the surface density of stars as a function of fundamental observables and quantities, as the redshift (after subsequent follow up to measure redshifts), the clustering properties (via e.g. the angular correlation function) etc.

- To study the dependence of the surface brightness distribution as a function of the color and other galaxy properties, including structural parameters.

2.3 Local Census of Dwarf Galaxies

P.I.: Michael Hilker

Dwarf galaxies are the most common type of galaxies in the universe. Whereas early-type dwarf galaxies (dwarf ellipticals (dEs) and dwarf spheroidals (dSphs)) dominate in numbers the galaxy population in the cores of galaxy clusters, late-type dwarf galaxies (mostly dwarf irregulars (dIrrs)) reside abundantly in the less dense environments like galaxy groups and the field. The exact fraction of dwarf galaxies is a challenging number for cold dark matter theories, especially in the context of galaxy formation within the numerous predicted dark matter sub-halos (i.e. the "missing-satellite" problem of Local Group dwarf galaxies). So far, only low surface brightness dwarf galaxies have been considered in the galaxy counts. But in the recent years it has been shown that there exist faint compact dwarf galaxies in nearby galaxy clusters that have been overlooked before. These so-called ultra-compact dwarf galaxies (UCDs) resemble globular clusters, but are up to 100 times more massive ($\geq 107 M_{sun}$) and have half-light radii of 10-30 pc. Their luminosities are comparable to those of nuclei of the most massive dwarf ellipticals or late-type spirals ($-11 > M_V > -14$ mag). The origin of UCDs is unclear. The most promising formation scenarios are:

1. UCDs might be the remnant nuclei of galaxies that have been disrupted in the cluster environment;

2. UCDs might have formed from the agglomeration of many young, massive star clusters that were created during ancient merger events;

3. UCDs are genuine small compact galaxies, maybe the successors of blue compact dwarf galaxies (BCDs).

Proving or discarding the one or other formation scenario requires a thorough search for UCDs in different environments, since almost nothing is known about the frequency of UCDs in groups and massive galaxy clusters.

The proposed VST survey, together with the public VST ATLAS survey, provides an excellent opportunity to derive a local census of all kinds of dwarf galaxies. Within about 100 Mpc ($\geq$ Coma cluster distance) dEs and dIrrs are resolved and can be identified by their surface brightness-magnitude relation or, in case of dEs, as low mass extension of the red sequence (see projects above).

The search for UCD candidates is restricted to a volume within 200-300 Mpc distance, given the limiting magnitude of the survey. Above about 4 Mpc UCDs cannot be resolved any more (assuming $r_h = 20$ pc and $1''$ seeing). M32-type compact ellipticals and BCDs can be detected upto a redshift of $z = 0.3$ and are resolved within $= sim20$ Mpc. The identification of UCD candidates requires a color as selection criterion which is provided by the extended g-band exposures of the VST ATLAS survey. In first place, we intend to search for compact dwarf galaxies in galaxy groups and clusters of known distances. Unresolved objects will be identified in individually adjusted color-magnitude windows in which those galaxies are expected (i.e. for UCDs: $-11.5 > M_r > -14.5$, $0.8 < (g - r) < 1.3$). Background subtraction will be done by applying the same selection criteria to selected control fields in neighbouring areas. The signal-to-noise of the overdensity of probable UCD candidates can be increased by stacking candidate samples of similar environments (loose groups, compact groups, small clusters, large clusters, etc.). This will allow to calculate the frequency of compact dwarfs compared to normal dwarfs as function of environment. The findings also will show whether the compact dwarfs can make a significant contribution to the overall number budget of dwarf galaxies, and thus might help to alleviate the missing-satellite problem.

Finally, the candidate lists of compact objects will form the basis for extensive follow-up spectroscopy with multi-object spectrographs (FLAMES, VIMOS, GMOS, IMACS, etc.). The one-by-one confirmation of small compact dwarf galaxies is the only way to provide a really clean sample. Moreover, the kinematics of UCDs within their environment might provide further clues to their origin.

2.4 Dwarf Galaxies in the Local Group

P.I.: Dante Minniti

New low luminosity, low surface brightness galaxies continue to be discovered in the Local Group. The latest example of the discovery of the lowest luminosity galaxies known using the SDSS (the dwarf spheroidal galaxies And IX and And X, satellites of M31 by Zucker et al, 2004, 2006) alerts us that similar objects may be still uncovered in the Southern hemisphere. Our survey has the capability to find galaxies as faint as $M_V \sim -8$, as well as sparse distant globular clusters and tidal tails of known globulars in the fields covered.

2.5 Gravitational lenses around giant elliptical galaxies.

P.I.: Vernica Motta

Gravitational lenses around giant elliptical galaxies have been used as astrophysical tools for studying distant galaxies and their environments. Simple models can be used to infer some properties of the lens, such the mass inside the Einstein ring, more accurately than any other astrophysical method. This is because the shape of an Einstein ring accurately determine the shape of the lens potential, breaking the degeneracies in the determination of the mass distributions or Hubble constants (if time delay is available) inferred from observations.

Given a set of lenses, the probability of forming rings of $\sim 1''$ from a population of sources depens on the angular size, the source redshift and the flux distribution. MIT-Greenbank-VLA survey has found 3 rings in a total of 4400 observed sources. Assuming that the optical and radio sources have the same rate of ring formation, this gives one ring for every 600 sources. In the range $22 < g < 23$ with $z > 1.0$ we estimate there are ~ 200.000 optical sources per square degree, so we infer that there should be ~ 200 optical rings per square degree. For a typical amplification of 5 for a ring, the sources with $22 < g < 23$ would produce ~ 40 rings per square degree with $g \sim 23$. The rings could be found by looking giant elliptical galaxies, using r band image to subtract the galaxy in g band and provide an homogeneous sample to study the lens potential of distant galaxies.

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